Radiation Damping for Speeding Up NMR Applications

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We address a problem of low repetition rate in nuclear magnetic resonance (NMR) applications. We suggest using a dynamical regime in the radiation damping that allows returning the nuclear magnetization to its equilibrium state during a time interval that is negligible compared to the spin relaxation time. We show theoretically and numerically that the radiation damping in the spin echo technique can be as effective as application of special radio-frequency (rf)-pulses. We obtain an analytical estimate for optimal damping that is consistent with our numerical simulations.

The problem of low repetition rate is one of the most important in many NMR applications. There are two main approaches for controlling the nuclear magnetic relaxation. The first is the application of an additional rf-pulse in the process of the echo formation. This pulse can return the nuclear magnetization to its equilibrium position. However, in order to implement this method the phase of the rf-pulse must be accurately adjusted relative to the phase of the transversal magnetization. The second method relies on the radiation field created by the resonant circuit interacting with the nuclear magnetization. In this method, the phase of the rf field produced by the circuit is automatically adjusted relative to the transversal magnetization. However, the effect of the radiation field is normally small because the radiation field is much smaller than the rf field. In [1], we demonstrated that the radiation damping can be as effective as the application of an additional rf-pulse. By increasing the duration of the spin echo and optimizing the resonant circuit parameters, one can restore the equilibrium position of the nuclear magnetization during the time of the echo formation, which is negligible compared with the spin relaxation time.

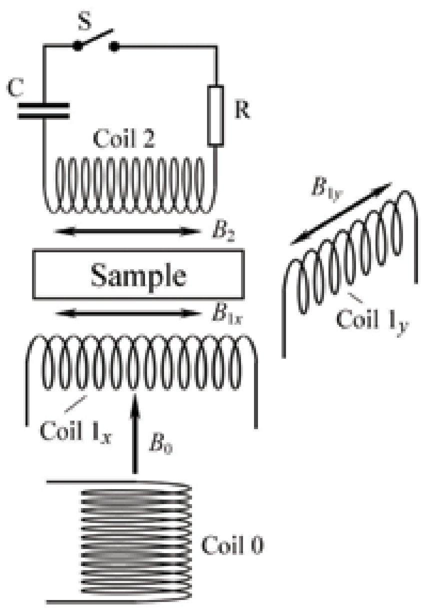

Fig. 1. Suggested setup.

Our consideration in [1] was done in the "dynamical" regime, when the characteristic time of the relaxation in the resonant circuit is much larger than the spin echo time. Our approach is valid for both weak and strong magnetic fields. We obtained an analytical estimate for the optimal conditions for radiation damping that is consistent with our numerical simulations. It is necessary to emphasize that in the dynamical regime considered in [1], the recovery of the longitudinal nuclear magnetization does not depend on the quality factor of the circuit because the recovery time is small compared to the time constant of the resonant circuit. This situation has not been studied in earlier publications on radiation damping. Also, we should note that from a theoretical point of view the fast radiation damping (FRD) obtained in [1] may not have an advantage compared to the application of an additional rf-pulse. Neither method interferes with signal processing methods for improving the signal-to-noise ratio. The optimal choice of a technique for speeding up the relaxation depends on the concrete experimental conditions (Fig. 1). Coil "0" produces a permanent non-uniform magnetic field, B_0, in the positive z-direction. Coil "1x" produces an oscillating field B_{1x} (rf-pulses) along the x-axis. It is also used for NMR detection (with weak radiation damping). Coil "1y" produces an oscillating field B_{1y} (rf-pulses) along the y-axis. It also can be used for NMR detection (with weak radiation damping). Coil 2 produces the oscillating field, B_2, along the x-axis, which causes radiation damping. Note that we use two coils, 1_x and 1_y, in order to produce circularly polarized rf-pulses. This is especially important if one is going to use an ultra-low permanent magnetic field, B_0. In the opposite case of high permanent magnetic field, instead of the circular polarized rf-pulses one can safely apply linearly polarized
rf-pulses. In this case one of the coils (1_x or 1_y) can be removed.

We propose the following scheme:

- At t=0 a rectangular rf $\pi/2$-pulse of duration, say, 10 µs is applied to the sample. At time t=1,010 µs, a rectangular rf π-pulse of duration of 10 µs is applied to the sample. At time t=3,020 µs, a rectangular rf-pulse of duration 10 µs is again applied to the sample.
- After the first pulse one observes a decaying signal of magnetic induction. Between the second and the third pulses one observes a spin echo. After the third pulse one again observes a spin echo (see Fig. 2).

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- Coil 2 is a part of an LCRS-circuit, (L stands for inductiance; S stands for a switch) with capacitance, C, and resistance, R. The switch, S, is closed (turned on) at t=3,030 µs, that is, after the third pulse. Before the third pulse, coil 2 does not influence the spin system. During the duration of the second spin echo, the radiation damping due to coil 2 drives the nuclear magnetization toward its equilibrium state.

Finally, in order to increase the repetition rate in various NMR applications we suggested the regime of FRD in the spin echo technique. We have shown that FRD can effectively restore the longitudinal nuclear magnetization during the time of the spin echo formation, which is small compared to the time constant of the resonant circuit and the spin relaxation time. We have obtained an estimate for the optimal choice of the resonant circuit parameters and confirmed it in our numerical experiments.

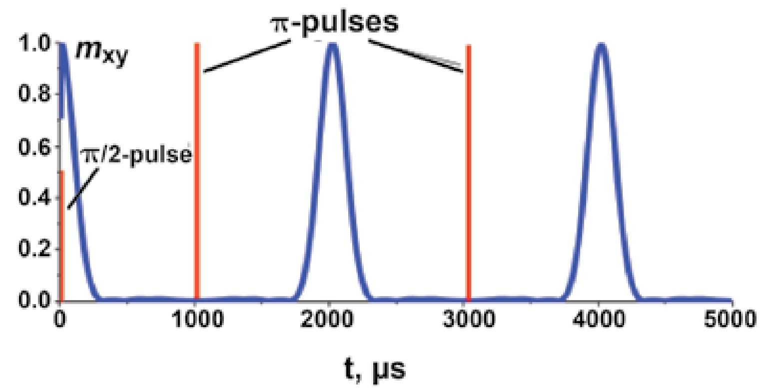

Fig. 2. Suggested spin echo sequence.

[1] Berman, G.P. et al., *Concepts Magn Reson* **40A**(4), 179 (2012).